EEC4122: Satellite Communication Systems

The Space Link

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Introduction

- link-power budget relates transmit power and received power and their differences
- Link-budget are given usually in decibels or decilog
- <u>**Equivalent Isotropic radiated power (EIRP)**</u>
- the maximum power flux density at some distance *r* from a transmitting antenna of gain G is: $\Psi_M = \frac{GP_S}{4\pi r^2}$
- For an isotropic radiator: it can produce the same power flux density with input power $G \times P_S = EIRP$
- It can be given in dBW: $[EIRP] = [P_S] + [G] \;\; dBW$
- <u>Example:</u> A satellite downlink at 12 GHz operates with a transmit power of 6 W and an antenna gain of 48.2 dB. Calculate the EIRP in dBW.

Introduction

- For a paraboloidal antenna: $G = \eta(10.472 \times f \times D)^2$
  - η → aperture efficiency (typically 0.55), f → in GHz and D → is reflector diameter in m
- <u>Example:</u> Calculate the gain in decibels of a 3-m paraboloidal antenna operating at a frequency of 12 GHz. Assume an aperture efficiency of 0.55.

Transmission Losses

- The [EIRP] may be thought of as the power input to one end of the transmission link, and the problem is to find the power received at the other end
- Losses can be classified into:
  - Constant losses
  - losses for clear weather (clear Sky) → do not vary significantly with time – from statistical data
  - Weather related (especially rainfall) → from statistical data – fluctuate with time – through fade margins

Free-space transmission

- resulting from the spreading of the signal in space
- Similar for the uplink and the downlink
- The power delivered to a matched receiver is this power-flux density multiplied by the effective aperture of the receiving antenna:

$$P_R = \Psi_M A_{eff} = \frac{EIRP}{4\pi r^2} \times \frac{\lambda^2 G_R}{4\pi} = EIRP \times G_R \times (\frac{\lambda}{4\pi r})^2$$

- In dB: $[P_R] = [EIRP] + [G_R] - 10log(\frac{4\pi r}{\lambda})^2 \quad dBW$ and $\lambda = \frac{c}{f}$
- The third term is free-space loss (FSL): $[FSL] = 10log(\frac{4\pi r}{\lambda})^2 \quad dB$
- FSL can be given as (exercise): $[FSL] = 32.4 + 20log(r) + 20log(f)$
  - f→ frequency in MHz and r → distance in Km
- The power received is: $[P_R] = [EIRP] + [G_R] - [FSL] \quad dBW$

Free-space transmission

- **<u>Example:</u>** The range between a ground station and a satellite is 42,000 km.
  - Calculate the free-space loss at a frequency of 6 GHz
  - Calculate the received power (for EIRP of previous example and G_R of 50 dB)

Free-space transmission

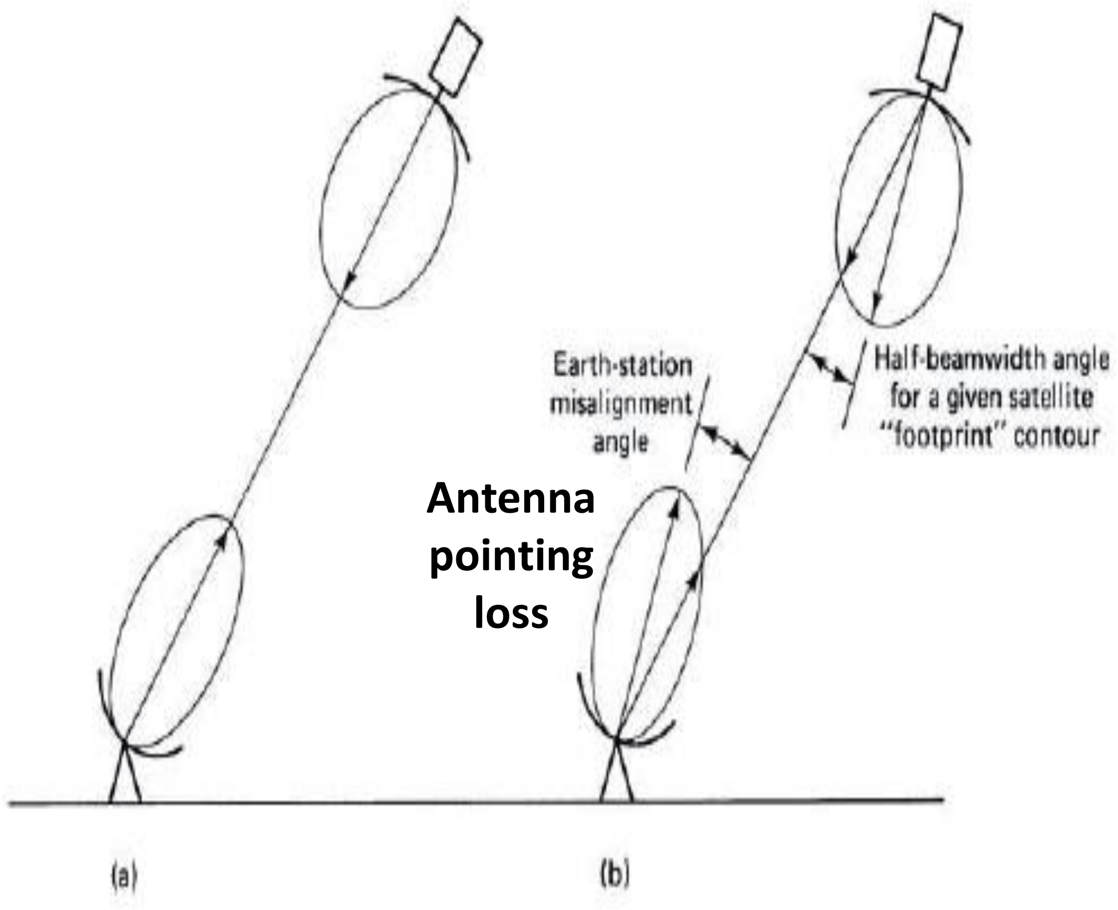
- Receiver antenna gain is inversely proportional to wavelength λ as $G_R = \eta(\frac{\pi D}{\lambda})^2$ hence increasing frequency results in increasing gain and received power
- However, FSL is inversely proportional to wavelength and increasing frequency resulting in increasing FSL !!!
- So, the two effects cancel each other and received power is independent of frequency for a **constant EIRP**
- But for a **constant transmit power,** the received power is proportional to the square of frequency

Feeder losses

- occur in the connecting waveguides, filters, and couplers denoted as receiver feeder loss (RFL)
- Also occur in the filters, couplers, and waveguides connecting the transmit antenna to the high-power amplifier output (considered If EIRP is not stated)

Antenna misalignment losses

- There are two possible sources of off-axis loss: one at the **satellite** and one at the **earth station** (antenna pointing loss, given in tables - few tenths of a decibel) → from statistical data
- Also one source of pointing losses is misalignment of the polarization direction (usually small)
- Both kinds are denoted together as [AML]
- Separate AML for UL and DL



Antenna misalignment losses

TABLE 12.1 Atmospheric Absorption Loss and Satellite Pointing Loss for Cities and Communities in the Province of Ontario

Location	Atmospheric absorption dB, summer	Satellite antenna pointing loss, dB	
		¼ Canada coverage	½ Canada coverage
Cat Lake	0.2	0.5	0.5
Fort Severn	0.2	0.9	0.9
Geraldton	0.2	0.2	0.1
Kingston	0.2	0.5	0.4
London	0.2	0.3	0.6
North Bay	0.2	0.3	0.2
Ogoki	0.2	0.4	0.3
Ottawa	0.2	0.6	0.2
Sault Ste. Marie	0.2	0.1	0.3
Sioux Lookout	0.2	0.4	0.3
Sudbury	0.2	0.3	0.2
Thunder Bay	0.2	0.3	0.2
Timmins	0.2	0.5	0.2
Toronto	0.2	0.3	0.4
Windsor	0.2	0.5	0.8

Fixed atmospheric and ionospheric losses

- Atmospheric gases result in losses by absorption, denoted as [AA]
- These losses usually amount to a fraction of a decibel
- The ionosphere introduces a depolarization loss, denoted as [PL]

$$[PL] = 20log(cos\theta_f) \text{ and } \theta_f \text{ is faraday rotation angle}$$

The Link-Power Budget Equation

- The power at receiver is: $[P_R] = [EIRP] - [LOSSES] + [G_R] \quad dBW$
- Losses for clear weather are:

$$[LOSSES] = [FSL] + [RFL] + [AML] + [AA] + [PL] \quad dB$$

- Where:

FSL → Free-space loss in dB (major source of losses)

RFL → Receiver feeder loss in dB

AML → Antenna misalignment loss in dB

AA → Atmospheric Absorption loss in dB

PL → Polarization loss in dB

The Link-Power Budget Equation

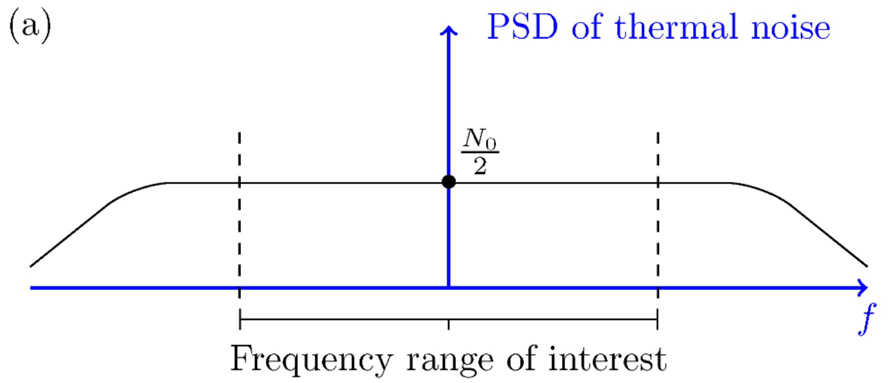
- **<u>Example:</u>** A satellite link operating at 14 GHz has receiver feeder losses of 1.5 dB and a free-space loss of 207 dB. The atmospheric absorption loss is 0.5 dB, and the antenna pointing loss is 0.5 dB. Depolarization losses may be neglected. Calculate the total link loss for clear-sky conditions.

System Noise

- The major source of electrical noise in equipment arises from the random thermal motion of electrons in various resistive and active devices in the receiver + thermal noise from lossy components of antennas
- Unless the signal is significantly greater than the electrical noise, amplification will be of no help because it will amplify signal and noise to the same extent (Don’t forget also amplifier noise !!!)
- Noise power from a thermal noise source is $P_N = kT_N B_N \quad watts$
  - K = 1.38×10^{-23} J/K → Boltzmann’s constant, T_N → equivalent noise temperature (K) and B_N→ equivalent noise bandwidth (Hz)
  - Noise bandwidth is 1.12 times the (-3 dB) bandwidth from frequency response curve

$$B_N = 1.12 \times B_{-3dB}$$

System Noise



- thermal noise has a flat frequency spectrum (noise power per unit bandwidth is constant)
- noise power spectral density N_0 is the noise power per unit bandwidth and given by: $N_0 = \frac{P_N}{B_N} = kT_N \quad J$
- Noise temperature is related to physical temperature but not equal
- There is other sources of noise other than thermal such as that produced in HPA due to signal products which is known as **intermodulation noise**

System Noise

- **Example:** An antenna has a noise temperature of 35 K and is matched into a receiver which has a noise temperature of 100 K.
  - Calculate (*a*) the noise power density and
    (*b*) the noise power for a bandwidth of 36 MHz.

System Noise

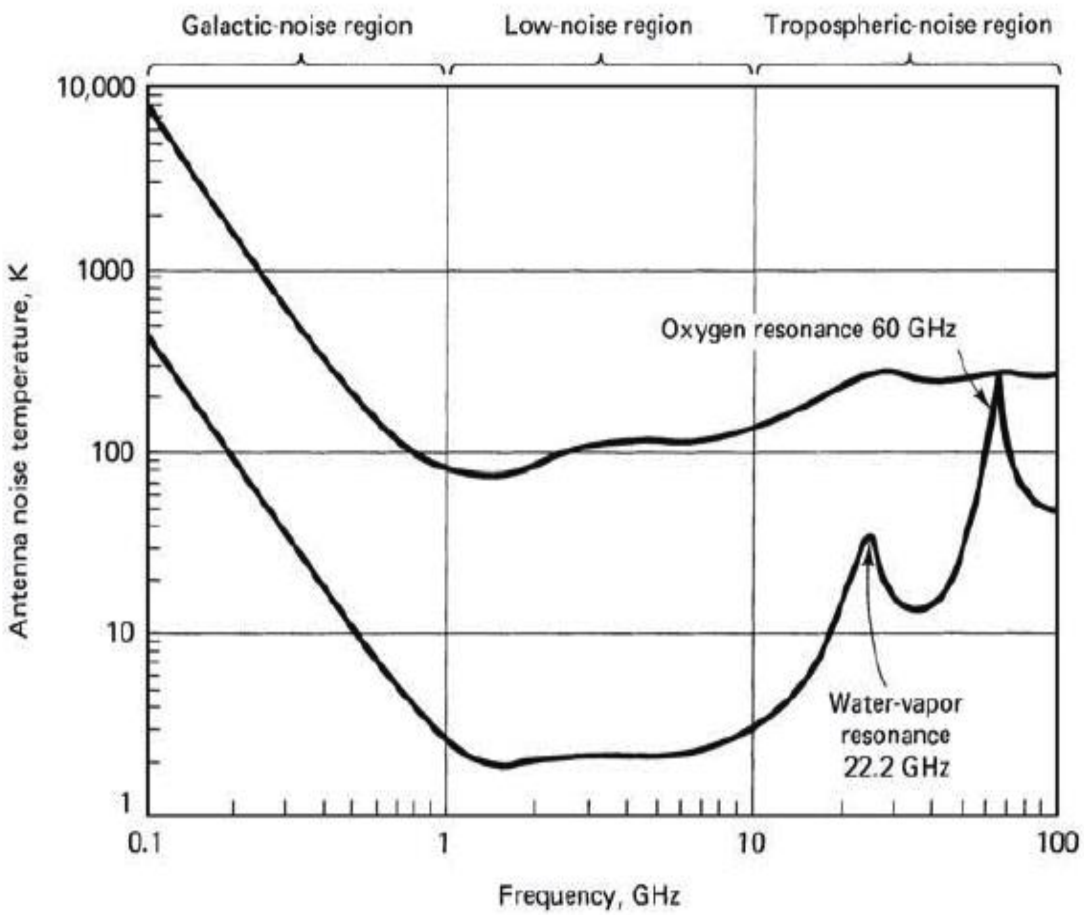
- **<u>1- Antenna noise</u>**
- Additional noise will be introduced by the satellite receive antenna and the ground station receive antenna
- Classified into: antenna losses noise and sky noise
  - **<u>Sky noise</u>**: due to the microwave radiation which is present throughout the universe and which appears to originate from matter in any form at finite temperatures that covers a wider spectrum than just the microwave spectrum
  - Sky noise for ground antenna is higher for small elevation angle due to the thermal radiation of the earth which sets a lower limit of about 5° at C band and 10° at Ku
  - Two resonant losses in the earth's atmosphere which coincide with the peaks in atmospheric absorption loss

System Noise

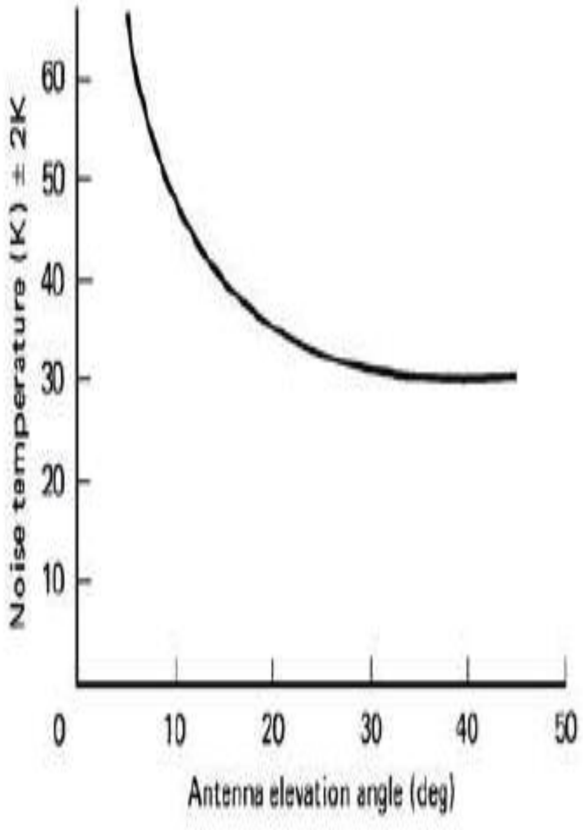
<u>1- Antenna noise</u>

- Any absorptive loss mechanism generates thermal noise, therefore, Rainfall degrades transmissions in two ways: It attenuates the signal, and it introduces noise (rainfall is more severe for Ku-band more than C-band)
- the equivalent noise temperature of the satellite antenna (receiving full radiation from earth), **excluding antenna losses**, is approximately 290 K
- The total antenna noise temperature is the sum of the equivalent noise temperatures of both kind of sources (antenna losses and sky noise)
- For large ground-based antennas, the total antenna noise temperature for Ku band (80 K) is higher than C band (60 K) under clear Sky

System Noise



1.8-m antenna operating in the Ku band

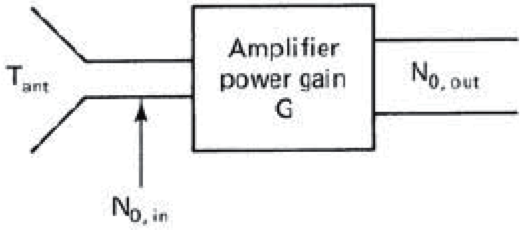


Operating frequency (GHz)	11.7-12.2
Polarization	Linear
Gain dB_i ± 0.2 dB at 11.95 GHz	45.0
Noise temperature (K)	
At 10° elevation	47
At 20° elevation	35
At 30° elevation	32
VSWR maximum	1.3
Isolation (dB)	35
Half-power beamwidth (deg)	0.91
Pattern envelope (PE) number	4374
Output flanges	WR-75

System Noise

2- Amplifier noise

- The input noise energy coming from the antenna is



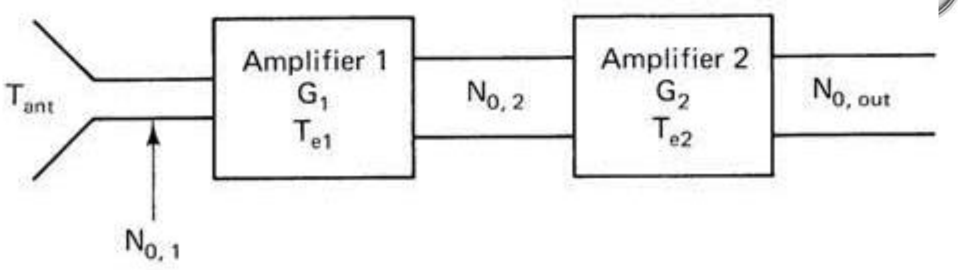
$$N_{0,ant} = kT_{ant}$$

- The output noise energy is that from both antenna plus the amplifier using equivalent input amplifier noise temperature as

$$N_{0,out} = kG(T_{ant} + T_e)$$

- Therefore, the total input noise is $N_{0,in} = \frac{N_{0,out}}{G} = k(T_{ant} + T_e)$
- T_e is in the range of 35 to 100 K (by measurement)

System Noise



<u>3- Amplifiers in cascade</u>

- The overall gain: $G = G_1 \times G_2$
- The total noise energy referred to amplifier 2 input is

$$N_{0,2} = kG_1(T_{ant} + T_{e1}) + kT_{e2}$$

- And the amplifier 1 noise input is:

$$N_{0,1} = \frac{N_{0,2}}{G_1} = k(T_{ant} + T_{e1} + \frac{T_{e2}}{G_1})$$

- The system noise temperature T_s can be defined as

$$T_S = T_{ant} + T_{e1} + \frac{T_{e2}}{G_1}$$

- In general: $T_S = T_{ant} + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots$
- Very important result, because in order to keep the overall system noise as low as possible, the first stage (usually an LNA) should have high power gain as well as low noise temperature

System Noise

4- Noise factor (F)

- is used to represent amplifier noise at room temperature (T_0 =290 K) such that the output noise from the amplifier is $N_{0,out} = FGkT_0$
- To relate amplifier noise temperature to its noise factor and from definition of noise factor (T_{ant} = T_0):

$$kG(T_0 + T_e) = FGkT_0 \rightarrow T_e = (F - 1)T_0$$

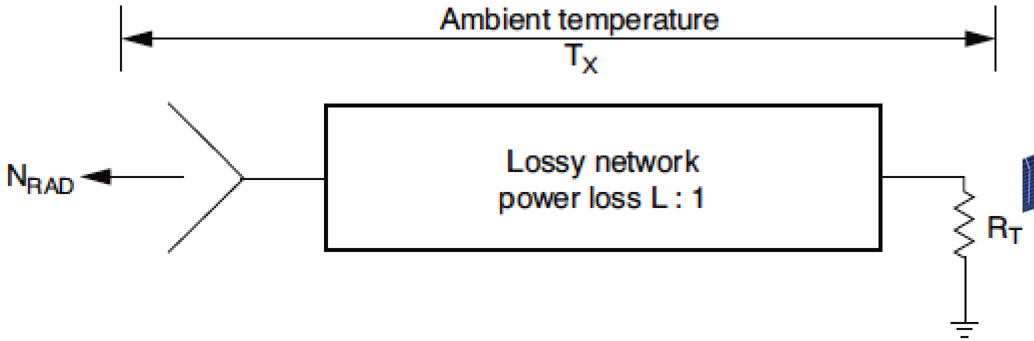
- Noise factor is specified for the main receiver unit
- Noise figure is expressed in dB as: $Noise\ Figure = [F] = 10log(F)\ \ dB$

System Noise

- **<u>4- Noise factor (F)</u>**

<u>Example:</u> An LNA is connected to a receiver which has a noise figure of 12 dB. The gain of the LNA is 40 dB, and its noise temperature is 120 K. Calculate the overall noise temperature referred to the LNA input.

System Noise



5- Noise temperature of absorptive networks (thermal)

- absorptive network is one which contains resistive elements such as Resistive attenuators, transmission lines, and waveguides which absorb energy from the signal and convert it to heat (even rainfall can be considered form of absorptive network)
- the noise energy radiated by the antenna is

$$N_{rad} = \frac{kT_x}{L} + kT_{NW,0}$$

  - T_x → is ambient temperature and $T_{NW,0}$ → is equivalent noise temperature
- But, the available noise energy which is fed into the antenna and radiated is: $N_{rad} = kT_x$

System Noise

- The equivalent noise temperature referred to network output is obtained by:

$$T_{NW,0} = T_x(1 - \frac{1}{L})$$

- Thus, the equivalent noise temperature of the network referred to the network input is:

$$T_{NW,i} = \frac{1}{L} \times T_{NW,0} = T_x(L - 1)$$

- If the lossy network should happen to be at room temperature (T_x = T_0) → F = L (noise factor is equal to power loss)

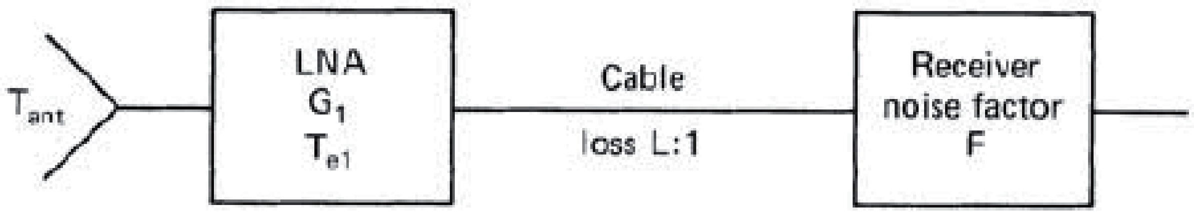
System Noise

6- Overall system noise temperature

- The system noise temperature referred to the input is

$$T_S = T_{ant} + T_{e1} + \frac{(L-1)T_0}{G_1} + \frac{L(F-1)T_0}{G_1}$$

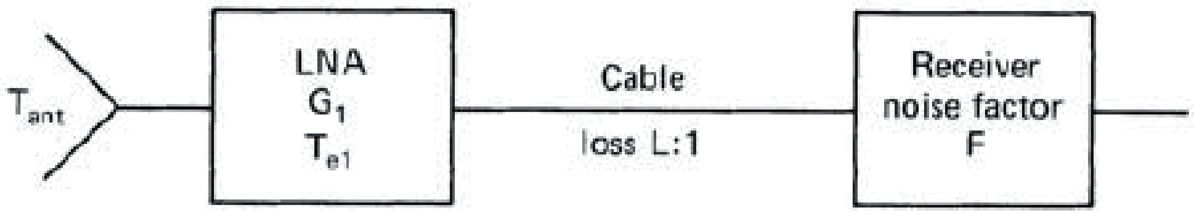
- LNA must be must be placed ahead of the cable, which is why one sees amplifiers mounted right at the dish in satellite receive systems !



(a)

System Noise

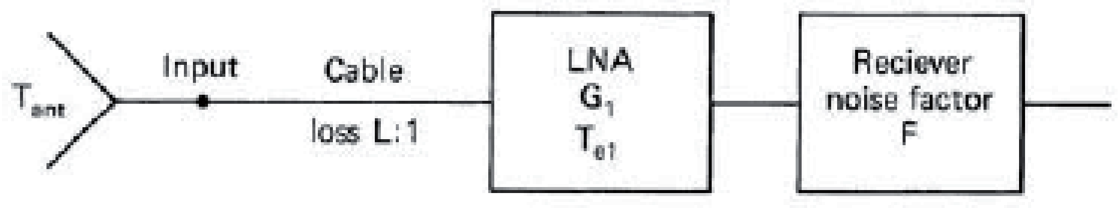
- **6- Overall system noise temperature**
- **Example:** For the shown system, the receiver noise figure is 12 dB, the cable loss is 5 dB, the LNA gain is 50 dB, and its noise temperature 150 K. The antenna noise temperature is 35 K. Calculate the noise temperature referred to the input.



(a)

System Noise

- **6- Overall system noise temperature**
- **Example:** Repeat the calculation when the system is arranged as shown below.



(b)

Carrier-to-Noise Ratio

- The ratio of carrier power to noise power at the receiver input

$$\left[\frac{C}{N}\right] = [P_R] - [P_N] \quad dB$$

$$\left[\frac{C}{N}\right] = [EIRP] + [G_R] - [LOSSES] - [k] - [T_S] - [B_N] \quad dB$$

- Another key parameter of receiver performance is G/T such that

$$[G/T] = [G_R] - [T_S] \quad dBK^{-1}$$

- Therefore, $\left[\frac{C}{N}\right] = [EIRP] + [G/T] - [LOSSES] - [k] - [B_N] \quad dB$
- Substituting: $\left[\frac{C}{N}\right] = \left[\frac{C}{N_0 B}\right] = \left[\frac{C}{N_0}\right] - [B_N]$ → $\left[\frac{C}{N_0}\right] = \left[\frac{C}{N}\right] + [B_N]$
- Therefore,

$$\left[\frac{C}{N_0}\right] = [EIRP] + [G/T] - [LOSSES] - [k] \quad dBHz$$

Carrier-to-Noise Ratio

- **<u>Example:</u>** In a link-budget calculation at 12 GHz, the free-space loss is 206 dB, the antenna pointing loss is 1 dB, and the atmospheric absorption is 2 dB. The receiver [G/T] is 19.5 dB/K, and receiver feeder losses are 1 dB. The EIRP is 48 dBW. Calculate the carrier-to-noise spectral density ratio

Sections 12.7 (The Uplink) and 12.8 (The Downlink) will be explained by Eng. Maram in the section (Pages: 367 ~ 375)

Effects of Rain

- All previous calculations are for clear-sky conditions
- Rainfall is the most significant cause of signal fading in both C and Ku
- Rainfall results in attenuation of radio waves by **scattering** and by **absorption of energy** from the wave
- Rain attenuation increases with increasing frequency
- The rain attenuation for horizontal polarization is considerably greater than for vertical polarization
- Rain attenuation data are usually available in the form of curves or tables
- Rain effects can be summarized as: wave attenuation, noise generation and wave depolarization

Effects of Rain

Ku band

- <u>at Thunder Bay:</u>
  - 99% → attenuation will be ≤ 0.2
  - 99.5% → attenuation will be ≤ 0.3
  - 99.9% → attenuation will be ≤ 1.3

TABLE 12.2 Rain Attenuation for Cities and Communities in the Province of Ontario

	Rain attenuation, dB		
Location	1%	0.5%	0.1%
Cat Lake	0.2	0.4	1.4
Fort Severn	0.0	0.1	0.4
Geraldton	0.1	0.2	0.9
Kingston	0.4	0.7	1.9
London	0.3	0.5	1.9
North Bay	0.3	0.4	1.9
Ogoki	0.1	0.2	0.9
Ottawa	0.3	0.5	1.9
Sault Ste. Marie	0.3	0.5	1.8
Sioux Lookout	0.2	0.4	1.3
Sudbury	0.3	0.6	2.0
Thunder Bay	0.2	0.3	1.3
Timmins	0.2	0.3	1.4
Toronto	0.2	0.6	1.8
Windsor	0.3	0.6	2.1

SOURCE: Telesat Canada Design Workbook.

Effects of Rain

- **<u>Uplink rain-fade margin</u>**
- Rainfall results in attenuation of the signal and an increase in noise temperature, degrading the $[C/N_0]$ at the satellite in two ways
- Noise increase is not highly considered in uplink because noise from hot earth masks any additional noise
- Through **uplink power control**, the power output from the satellite may be monitored and the power output from any given earth station may be increased if required to compensate for rainfall fading
- Thus, HPA must have reserve power to compensate fading
- Rain-fade margins are given through tables
- Example: Ottawa from table

Effects of Rain

- **<u>Downlink rain-fade margin</u>**
- Rainfall introduces attenuation by scattering or absorption which introduces noise
- The power loss ratio corresponding to the rain attenuation caused by absorption is denoted as [A] dB and the effective noise temperature of the rain is $T_{rain} = T_a(1 - \frac{1}{A})$
- T_a is **apparent absorber temperature** which is
  - Function of physical temperature of the rain and the scattering effect of the rain cell on the thermal noise incident upon it
  - lies between 270 and 290 K
- The total sky-noise temperature is $T_{SKY} = T_{CS} + T_{rain}$
- Therefore, rainfall affects $[C/N_0]$ in two ways: attenuating carrier wave and increasing sky noise temperature

Effects of Rain

- **<u>Example:</u>** Under clear-sky conditions, the downlink [C/N] is 20 dB, the effective noise temperature of the receiving system being 400 K. If rain attenuation exceeds 1.9 dB for 0.1 percent of the time, calculate the value below which [C/N] falls for 0.1 percent of the time. Assume Ta = 280 K.

Effects of Rain

- <u>Exercise:</u> Prove that for Downlink (entirely absorptive):

$$\left(\frac{N}{C}\right)_{rain} = \left(\frac{N}{C}\right)_{CS}\left(A + (A-1)\frac{T_a}{T_{S,CS}}\right)$$

  - A → absorptive attenuation (ratio)
  - CS → Clear-Sky
  - T_a → apparent absorber temperature
  - $T_{S,CS}$ → System noise temperature in Clear-Sky

Effects of Rain

- **<u>For low frequencies (6/4 GHz) and low rainfall rates (< 1 mm/h)</u>**
  - the rain attenuation is almost entirely absorptive
- **<u>At higher rainfall rates</u>**
  - scattering becomes significant especially at high frequencies
- **<u>If scattering and absorption are both significant</u>**
  - Total attenuation of both is used to calculate reduction in carrier power
  - absorptive attenuation is used to calculate increase in noise temperature
- A minimum value of [*C*/*N*] is required for satisfactory reception
- **No downlink power control**, but, increasing antenna gain or using receiver with low noise may compensate for rain-fade

Effects of Rain

- <u>Example: </u>In an FM satellite system, the clear-sky downlink [*C*/*N*] ratio is 17.4 dB and the FM detector threshold is 10 dB
- (*a*) Calculate the threshold margin at the FM detector, assuming the threshold [*C*/*N*] is determined solely by the downlink value.
- (*b*) Given that T_a 272 K and that $T_{S,CS}$ 544 K, calculate the percentage of time the system stays above threshold. The curve beside may be used for the downlink, and it may be assumed that the rain attenuation is entirely absorptive.

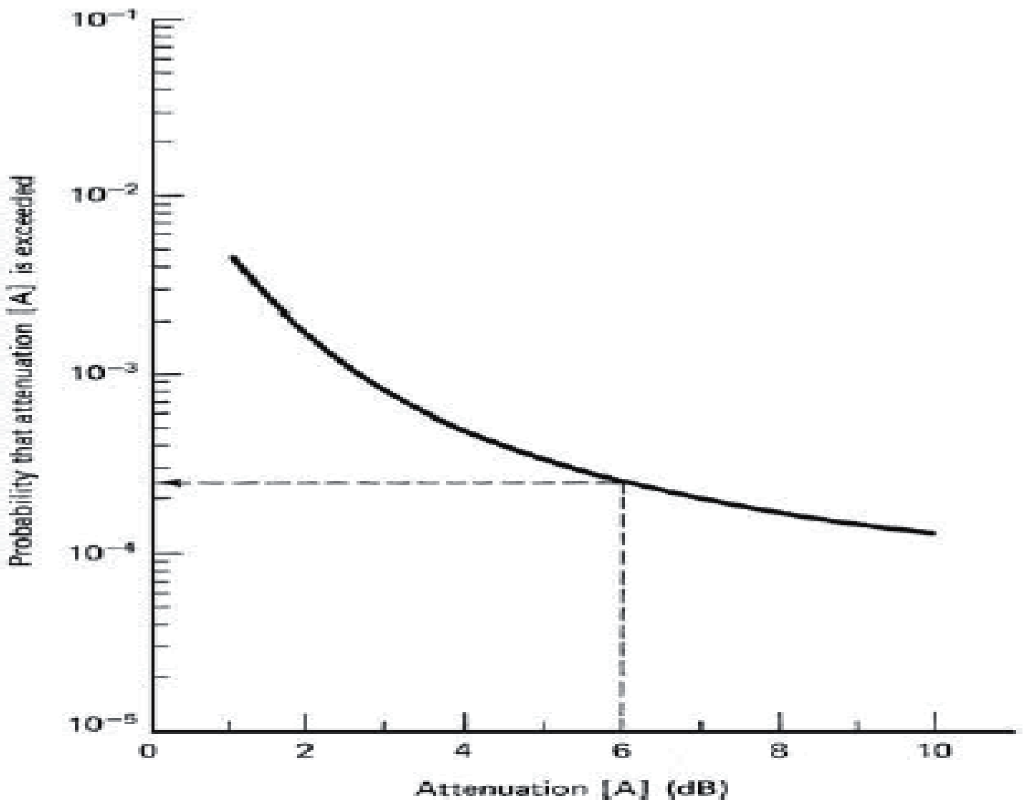


Figure 12.8 Typical rain attenuation curve used in Example 12.17.

Inter-Satellite Links

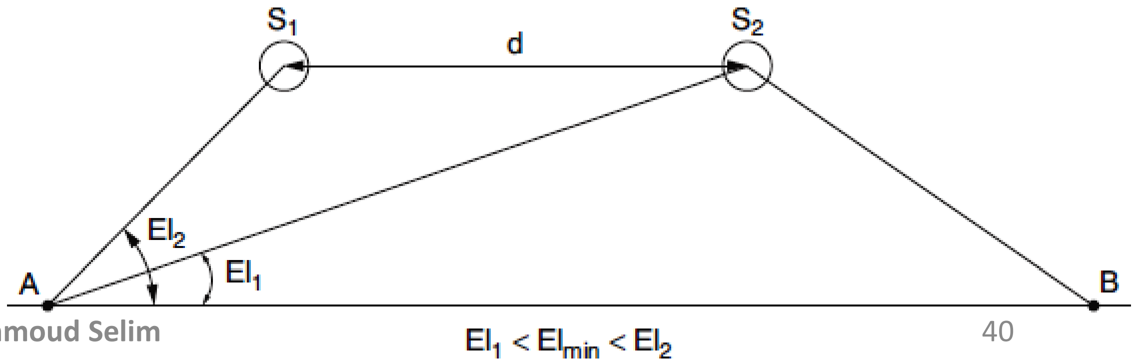
- Radio frequency or optical links that provide a connection between satellites without the need for intermediate ground stations
- There are three useful kinds of links:
  - low earth orbiting (LEO) satellites—LEO ↔ LEO
  - geostationary earth orbiting (GEO) satellites—GEO ↔ GEO
  - LEO ↔ GEO
- To solve the problem initiated from the limit of visibility as set by the

minimum angle of elevation

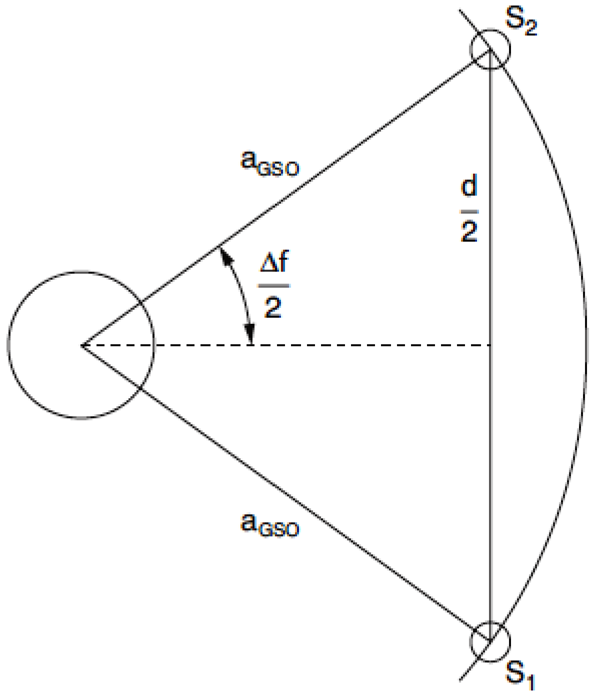
- Thus, a long distance link between

two earth stations can be achieved
(very good solution for inter-continental service)

- Europe-Asia link requires three hops (3 Uplinks and 3 Downlinks !!!), but using ISL → only one uplink and one downlink



Inter-Satellite Links



- Advantages can be summarized as follows:
  - Intercontinental services can be provided without need for multi-hops
  - Need only one uplink and downlink
  - The ISL frequencies are well outside the standard uplink and downlink bands
  - The cost of the ISL is more than offset by not having to provide the additional earth stations
  - Large-distance links (d) can be achieved such that

    $d = 2a_{GSO} sin\frac{\Delta\phi}{2}$ and $\Delta\phi$ is the longitudinal separation between satellites

Inter-Satellite Links

- Ex: For the (CONUS) arc at 55° and 136°, d for ISL is 54767 km where for a 3-hop involving 3 uplinks and 3 downlinks it spans 246000 km!!!
- GEO satellites are often arranged in clusters at some nominal longitude (like Echostar at 119°) and The separation between satellites is typically about 100 km (0.136°)
- All satellites in the cluster are within the main lobe of the earth-station antenna
- LEO satellites are not continuously visible from a given earth location so a network of satellites is required to provide continuous coverage of any region
- A typical LEO satellite network will utilize a number of orbits, with equi-spaced satellites in each orbit
- Ex: the Iridium system uses 6 orbital planes with 11 equi-spaced satellites in each plane, for a total of 66 satellites
- Radio frequency ISLs make use of frequencies that are highly attenuated by the atmosphere, so that interference to and from terrestrial systems using the same frequencies is avoided

Inter-Satellite Links

- Antennas for the ISL are steerable and the beamwidths are sufficiently broad to enable a tracking signal to be acquired to maintain alignment
- Disadvantage of RF ISL: low bit rate
- Advantage of optical ISL: high data rates of 1 Gbps and optical equipment is smaller and more compact

TABLE 12.3 ISL Frequency Bands

Frequency band, GHz	Available bandwidth, MHz	Designation
22.55–23.55	1000	ISL-23
24.45–24.75	300	ISL-24
25.25–27.5	2250	ISL-25
32–33	1000	ISL-32
54.25–58.2	3950	ISL-56
59–64	5000	ISL-60
65–71	6000	ISL-67
116–134	18000	ISL-125
170–182	12000	
185–190	5000	